Top (and bottom-quark) production asymmetries at the Tevatron

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Top at Twenty Workshop
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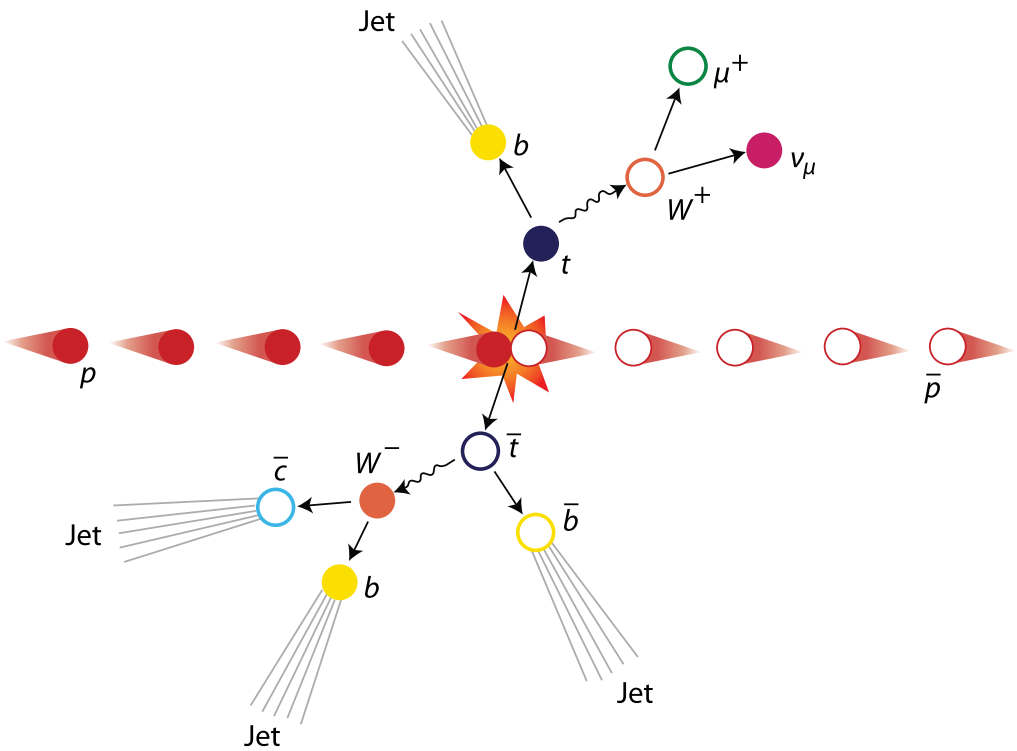
Outline

- $t\bar{t}$ forward–backward asymmetry
  - Complementary measurements at the Tevatron and the LHC
  - Some comments on why this has been a hot topic in the last few years
- $A_{\mathrm{FB}}^{t\bar{t}}$ measurements based on top reconstruction
- A_{FB}^{ℓ} and $A_{\mathrm{FB}}^{\Delta\eta}$ measurements based on leptons
- $b\bar{b}$ asymmetry measurements
- Conclusions

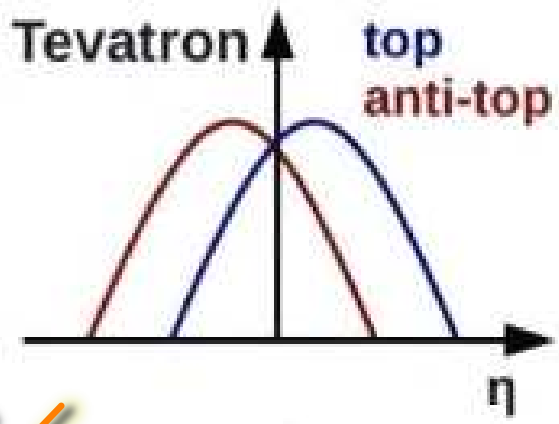
Forward–backward asymmetry

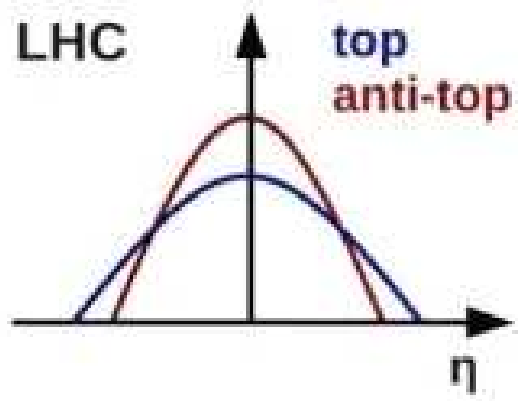


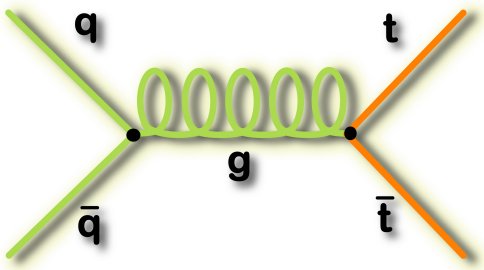
- $p\bar{p}$ collision at Tevatron
- A_{FB} measurements are simply answering:

  Does the top quark prefer the proton direction or the opposite?

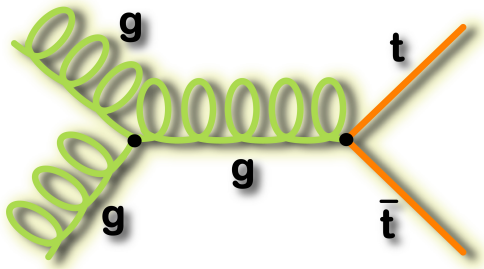
Complementarity between the Asymmetry at the Tevatron and the LHC







(a)



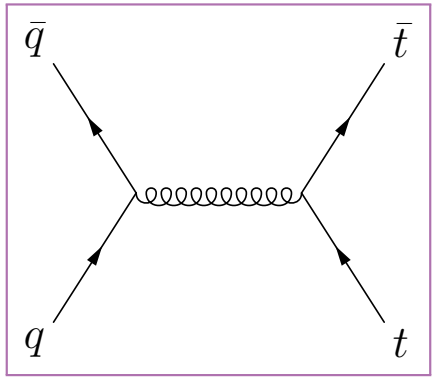
(b)

- $p\bar{p}$ collision at Tevatron instead of pp collision at LHC
- Asymmetry from $q\bar{q}$ annihilation (a)
  - Tevatron $t\bar{t}$ production dominated by $q\bar{q}$ annihilation (85%, a)
  - LHC dominated by gluon fusion (90%, b)
- Sizeable effect at Tevatron, very small asymmetry (central vs. outer) at LHC

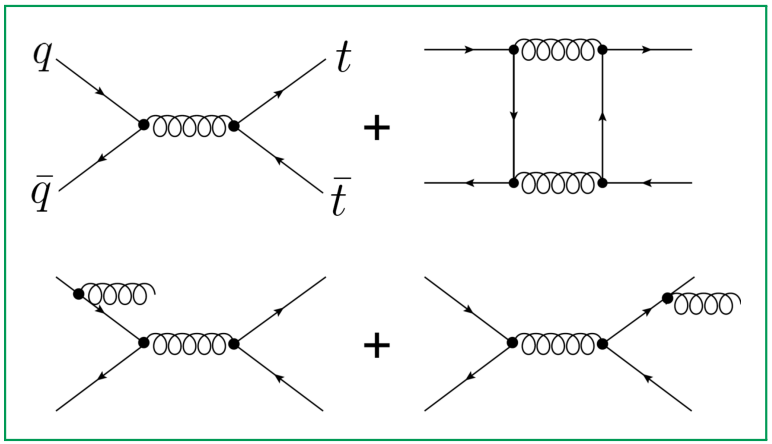
For details about asymmetry measurements at LHC, see next talk

A_{FB} at Tevatron: Why important?

Why this is important?



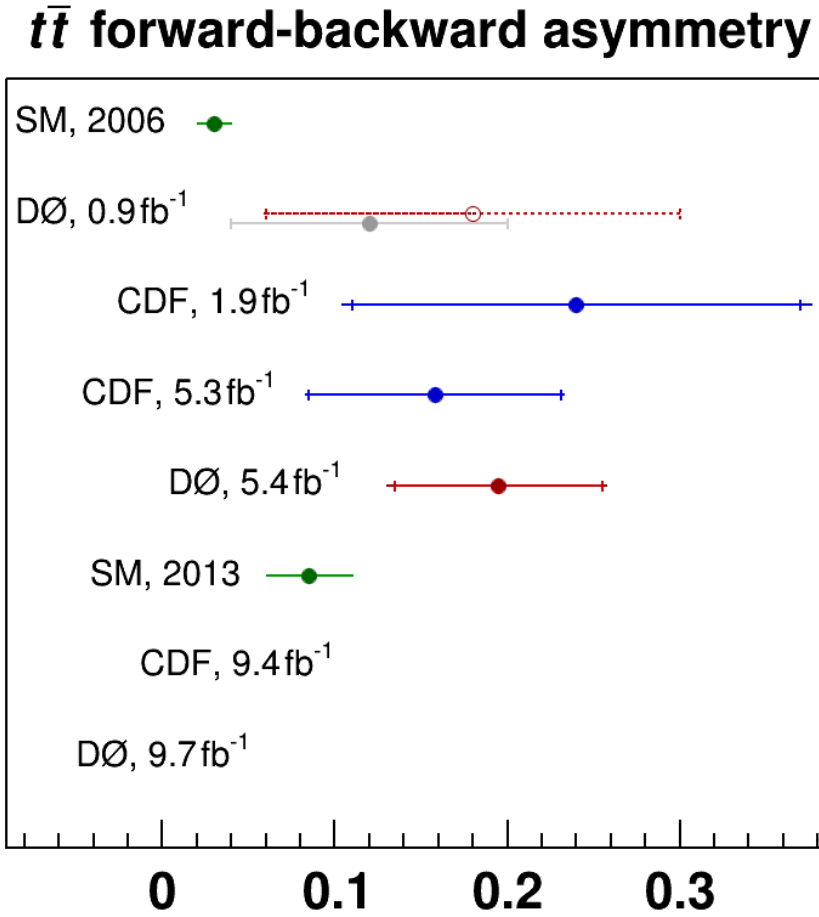
- No net asymmetry in leading order diagram
  - Asymmetry only from higher order effects
- Slight asymmetry starting from next-to-leading order (NLO) effects
  - Interference among diagrams
- Non-negligible EW correction and higher order QCD corrections complicate the calculation
  - Details in Alex Mitov's talk for NNLO calculation
- **Precision probe of SM production predictions with large mass particles**



A_{FB} at Tevatron: Why interesting?

Why this is interesting?

- First set of measurements showed larger-than-SM values
- Higher than SM asymmetry leaves room for various beyond-SM models
  - s-channel axigluon, t-channel W', Z', etc.
- Need to squeeze every drop from Tevatron data to understand this potential anomaly

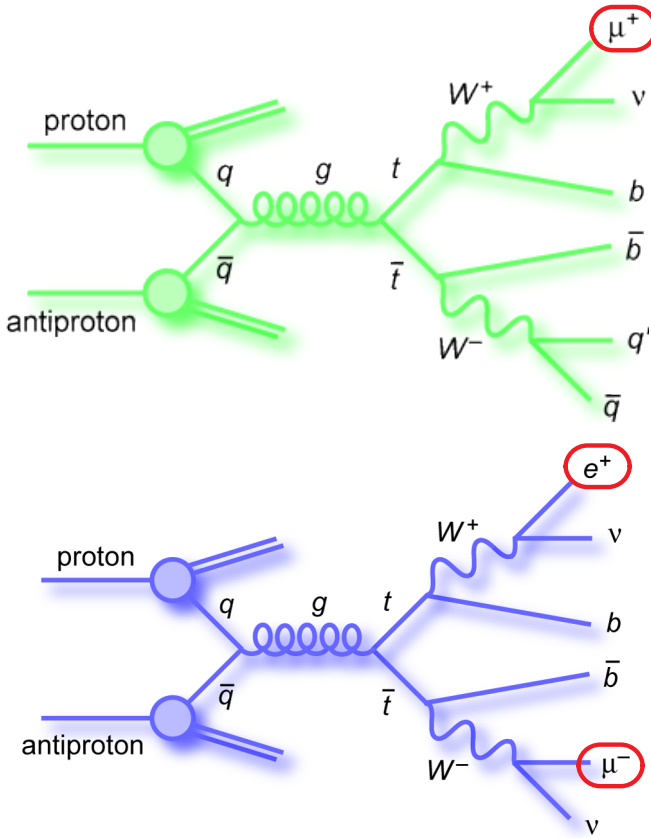


- **All results shown based on full Tevatron run II data**

Ways to measure asymmetry

Three categories of asymmetry measurements

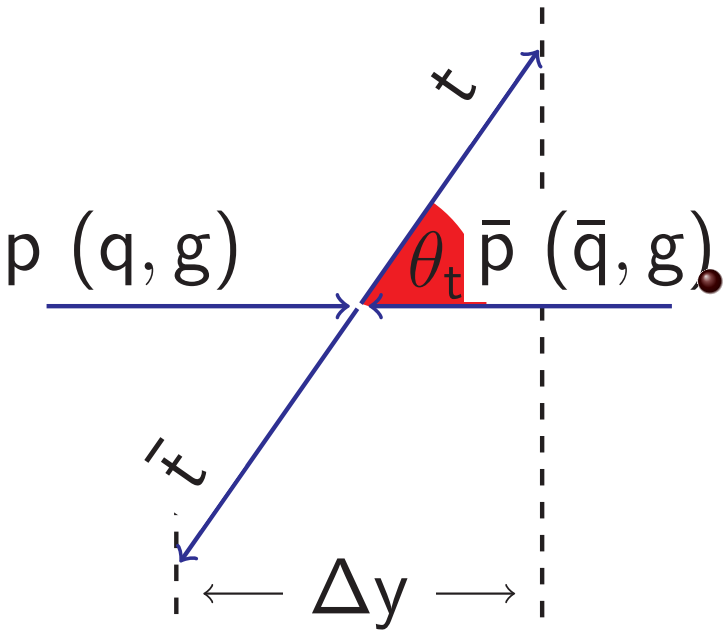
- Fully reconstructed top quarks
  - Can measure asymmetry of top rapidity
  - More details from the cross section as a function of production angle
- Top leptonic asymmetry and lepton pair asymmetry
  - A cleaner measurement from the leptons from top cascade decays
- A_{FB} in $b\bar{b}$ production
  - An independent test of the same SM dynamics, and also potentially look for new physics



$A_{FB}^{t\bar{t}}$

A_{FB} measurement based on top reconstruction

Definition of $A_{FB}^{t\bar{t}}$



$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

- NLO predictions from 0.05 to 0.125 (arxiv:1406.1798 and refs therein)
- One NNLO QCD prediction: $A_{FB}^{t\bar{t}} = 0.095 \pm 0.007$ (arxiv:1411.3007)

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

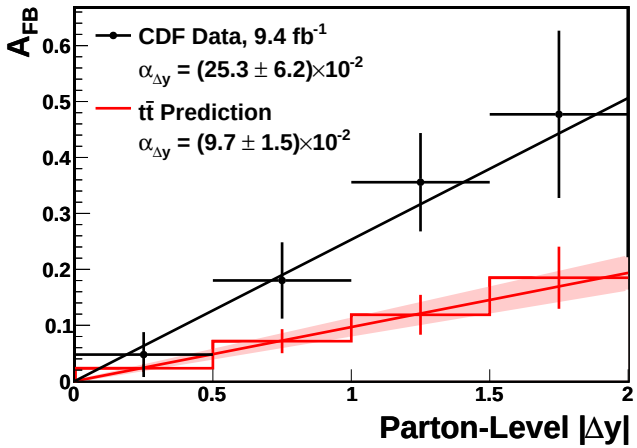
$$\Delta y = y_t - y_{\bar{t}}$$

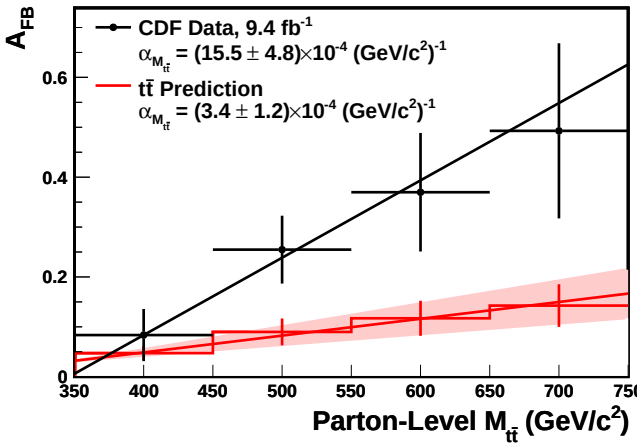
- All results shown are unfolded back to parton level, to be directly compared with theoretical predictions

$A_{FB}^{t\bar{t}}$: CDF lepton+jets

$$A_{FB}^{t\bar{t}} = 0.164 \pm 0.039(\text{stat}) \pm 0.026(\text{syst})$$

- Top reconstruction based only on kinematics
- Unfolding based on singular value decomposition (SVD)
- Predictions on plots at NLO (predate NNLO predictions)
- Inclusive $A_{FB}^{t\bar{t}}$ 1.5σ higher than NNLO
- Differential asymmetries show 2.8σ ($|\Delta y|$) and 2.4σ ($m_{t\bar{t}}$) differences w.r.t. NLO SM



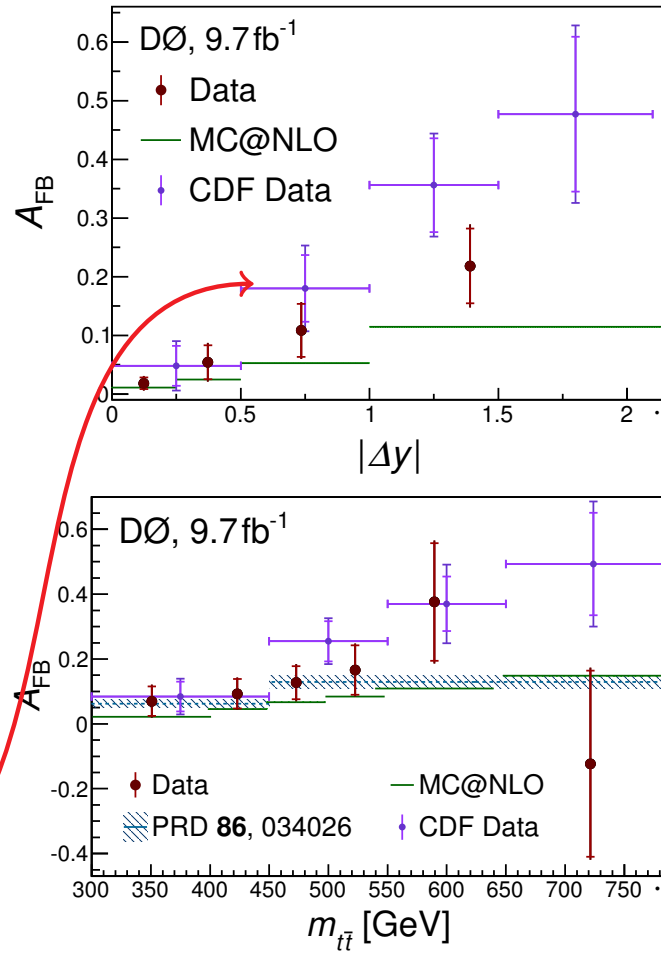


PRD 87, 092002 (2013)

$A_{FB}^{t\bar{t}}$: D0 lepton+jets

$$A_{FB}^{t\bar{t}} = 0.106 \pm 0.030$$

- New kinematic fitter (NIM A 736 (2014) 169)
- Including lepton+3 jets channel with partial reconstruction
- Unfolding implemented with TUnfold
- Inclusive A_{FB} agrees with NNLO SM
- A_{FB} vs. $|\Delta y|$ rises above NLO prediction
  - Same trend as in CDF lepton+jets
- Good agreement in A_{FB} vs. $m_{t\bar{t}}$

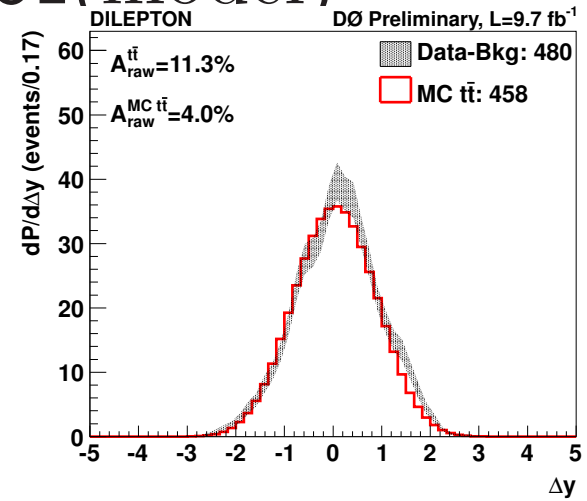


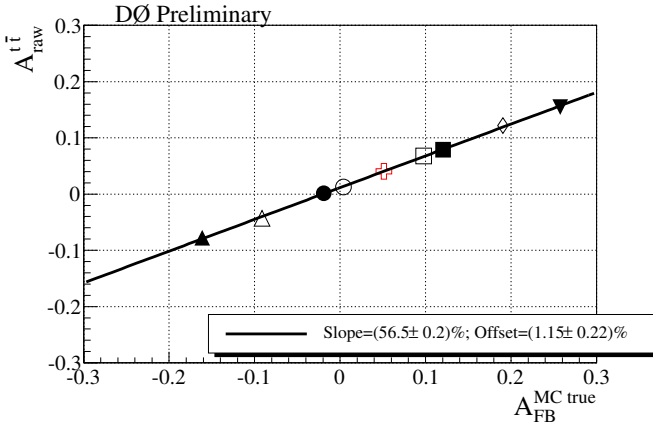
PRD 90, 072011 (2014)

$A_{FB}^{t\bar{t}}$: D0 dilepton

$$A_{FB}^{t\bar{t}} = 0.180 \pm 0.069(\text{tot.}) \pm 0.051(\text{model})$$

- Top reconstruction based on matrix-element (ME) technique
- Calibration with MC reweighting for parton-level asymmetry
- Consistent with SM prediction and CDF/D0 lepton+jets results
- Not enough power to measure differential A_{FB}



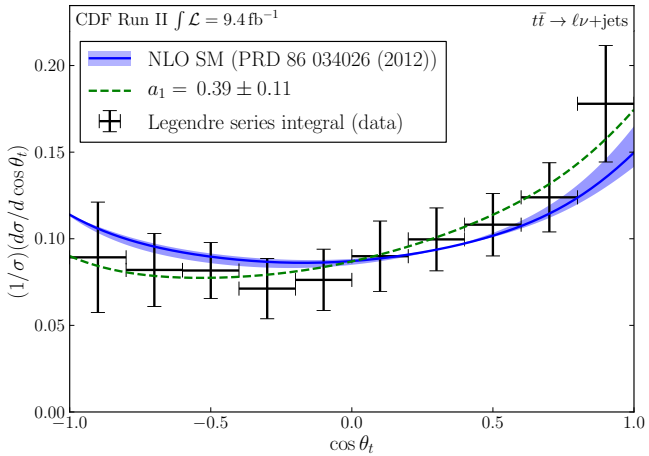


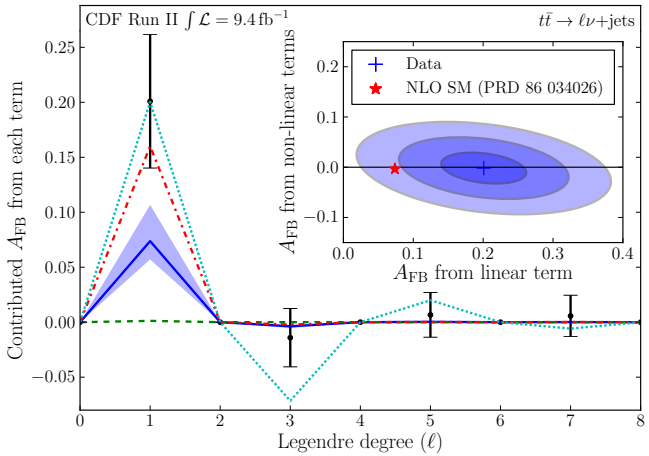
D0 note 6445-CONF

$d\sigma/d\cos\theta_t$: CDF lepton+jets

$$a_1(\text{obs}) = 0.40 \pm 0.12 \text{ w/ } a_1(\text{pred}) = 0.15^{+0.07}_{-0.03}$$

- Characterize the differential cross section with Legendre polynomials
$$\frac{d\sigma}{d\cos\theta_t} = \Sigma_\ell a_\ell P_\ell(\cos\theta_t)$$
- Good agreement with NLO SM prediction except a_1 (the linear term)
- 2.1σ excess in a_1 from NLO SM
- Naively favors models with strong s-channel components





PRL 111, 182002 (2013)

A_{FB}^{ℓ} and $A_{FB}^{\Delta\eta}$

- Next: **A_{FB} measurements based on leptons from top decays: A_{FB}^{ℓ} and $A_{FB}^{\Delta\eta}$**

A_{FB}^{ℓ} and $A_{FB}^{\Delta\eta}$

- Leptonic A_{FB}

$$A_{FB}^{\ell} = \frac{N(q_\ell \eta_\ell > 0) - N(q_\ell \eta_\ell < 0)}{N(q_\ell \eta_\ell > 0) + N(q_\ell \eta_\ell < 0)}$$

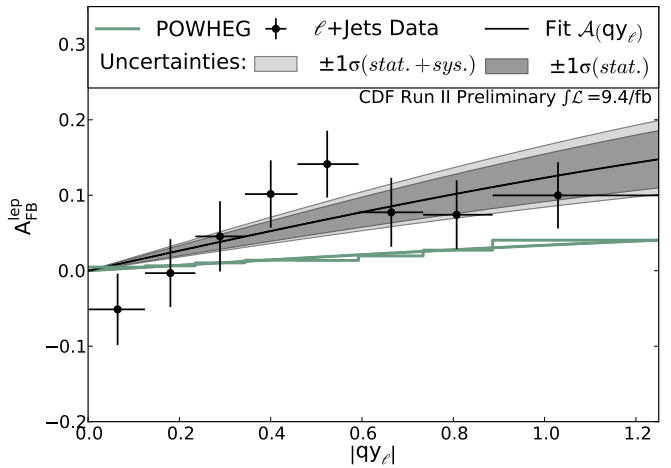
- Also lepton pair A_{FB} defined with lepton η difference, only in dilepton
  - Lepton angles precisely measured
  - Tend to follow direction of parent tops
  - Also carry information about top spin
- $A_{FB}^{\ell}(\mathrm{NLO, SM}) = 0.038 \pm 0.003$
  $A_{FB}^{\Delta\eta}(\mathrm{NLO, SM}) = 0.048 \pm 0.004$
  PRD 86, 034026 (2012)

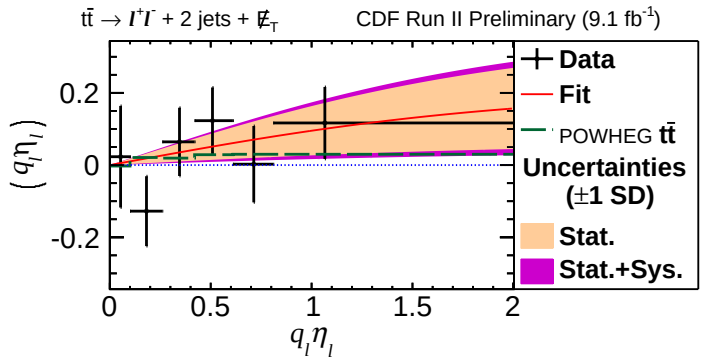
A_{FB}^{ℓ}: CDF lepton+jets & dilepton

$$A_{FB}^{\ell}(\mathrm{L+J}) = 0.094^{+0.032}_{-0.029} \;\&\; A_{FB}^{\ell}(\mathrm{DIL}) = 0.072 \pm 0.060$$

$$A_{FB}^{\ell}(\mathrm{CDF}) = 0.090^{+0.028}_{-0.026}$$

- Differential asymmetry ($A_{FB}^{\ell}(q_\ell \eta_\ell)$) is best sensitive observable
- Corrected for detector effects
- Parton-level measurement based on $a \cdot \tanh(\frac{1}{2} q_\ell \eta_\ell)$ modeling of $A_{FB}^{\ell}(q_\ell \eta_\ell)$
  - Methodology validated in PRD 90, 014040 (2014)
- CDF combination based on BLUE
- 2σ higher than NLO SM





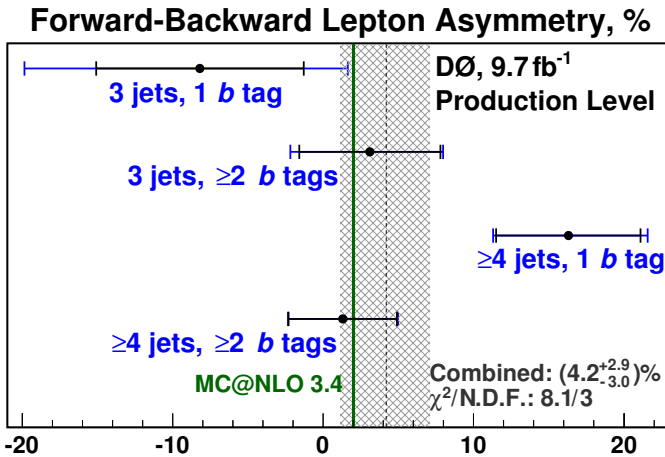
PRD 88, 072003 (2013)

PRL 113, 042001 (2014)

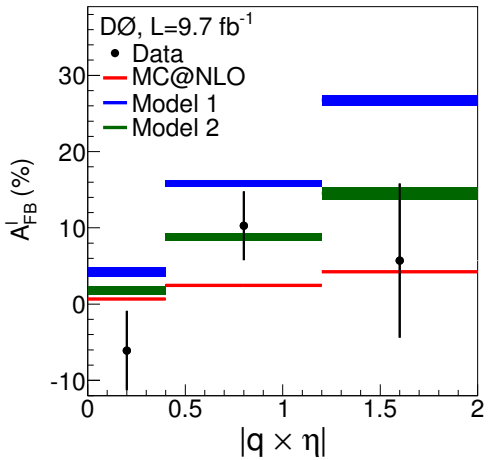
A_{FB}^{ℓ}: D0 lepton+jets & dilepton

$$A_{FB}^{\ell}(\mathrm{L+J}) = 0.050^{+0.034}_{-0.037} \;\&\; A_{FB}^{\ell}(\mathrm{DIL}) = 0.044 \pm 0.039$$

$$A_{FB}^{\ell}(\mathrm{D0}) = 0.047 \pm 0.027$$



- Including lepton + 3 jets in L+J measurement
- Detector effect corrected with bin-by-bin correction
- Parton-level extrapolation based on MC-derived multiplication
- D0 combination based on BLUE
- Consistent with NLO SM

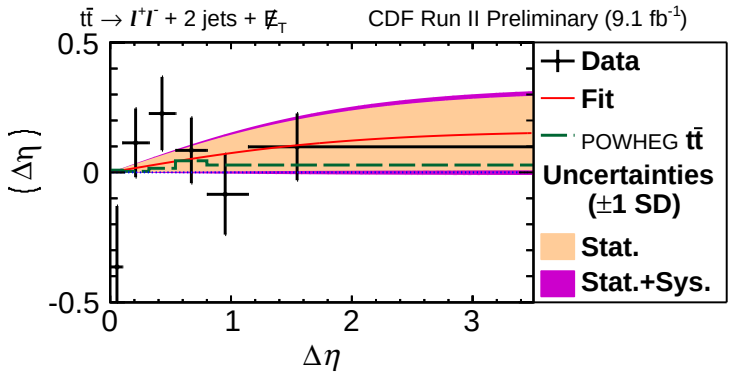


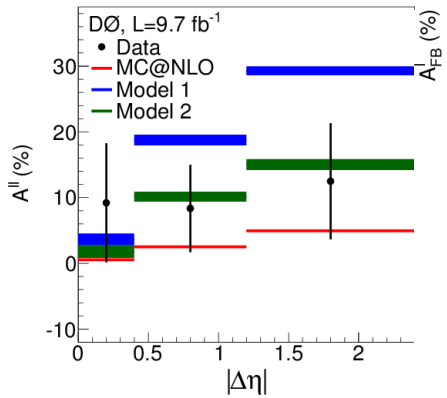
PRD 90, 072001 (2014)
PRD 88, 112002 (2013)

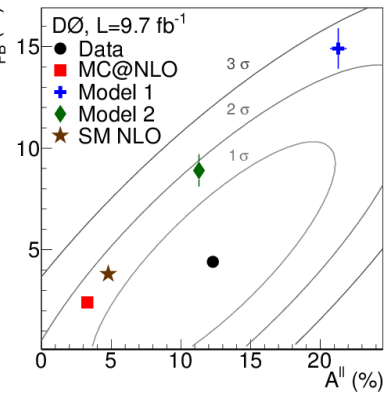
$A_{FB}^{\Delta\eta}$

$$A_{FB}^{\Delta\eta}(\mathrm{CDF}) = 0.076 \pm 0.082 \;\&\; A_{FB}^{\Delta\eta}(\mathrm{D0}) = 0.123 \pm 0.056$$

- CDF measurement based on $a \cdot \tanh(\frac{1}{2}\Delta\eta)$ modeling of differential asymmetry ($A_{FB}^{\Delta\eta}(\Delta\eta)$)
- D0 measurement based on bin-by-bin correction and MC-derived extrapolation
- Both results consistent with NLO SM
- A_{FB}^{ℓ} and $A_{FB}^{\Delta\eta}$ correlated







PRL 113, 042001 (2014)

PRD 88, 112002 (2013)

$A_{FB}^{b\bar{b}}$

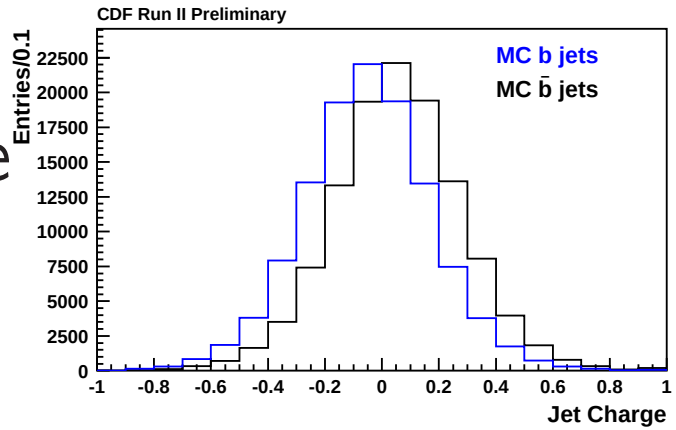
$b\bar{b}$ asymmetry

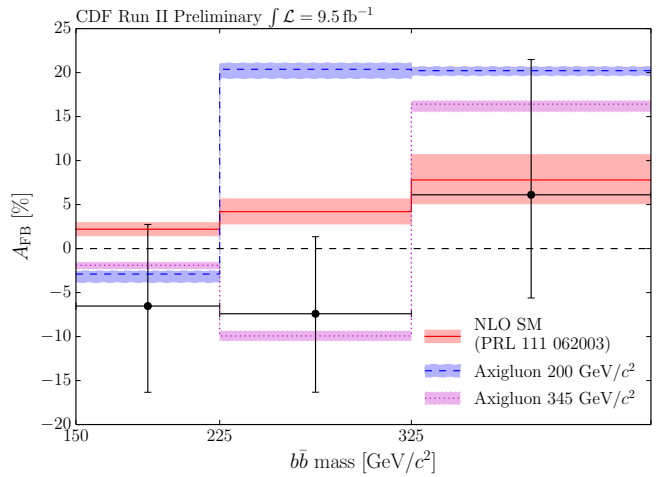
$A_{\mathrm{FB}}^{b\bar{b}}$

- If the $t\bar{t}$ production asymmetry is indeed non-SM, there is good reason to believe there should be observable effects in $b\bar{b}$ asymmetry
- Sensitive to axigluon hypothesis below $t\bar{t}$ threshold
- Next: Present three measurements of $A_{\mathrm{FB}}^{b\bar{b}}$ using three different techniques
  - High mass $A_{\mathrm{FB}}^{b\bar{b}}$ ($m_{b\bar{b}} > 150\mathrm{GeV/c^2}$) using jet charge techniques (CDF)
  - Low mass $A_{\mathrm{FB}}^{b\bar{b}}$ ($m_{b\bar{b}} > 40\mathrm{GeV/c^2}$) using soft muon tags (CDF)
  - $A_{\mathrm{FB}}(B^{\pm})$ with $B^{\pm} \to J/\psi(\to \mu^+\mu^-)K^{\pm}$ (D0)

$A_{FB}^{b\bar{b}}$ at high mass

- Use momentum-weighted track charge sum to differentiate between b and $\bar{b}$
- Measure $A_{FB}^{b\bar{b}}$ in three $b\bar{b}$ mass bins: [150, 225], [225, 325] and [325,∞)
- Use Bayesian techniques to extract hadron-jet level asymmetry
- Result consistent with SM prediction
- Exclude 200 $\mathrm{GeV/c^2}$ axigluon models

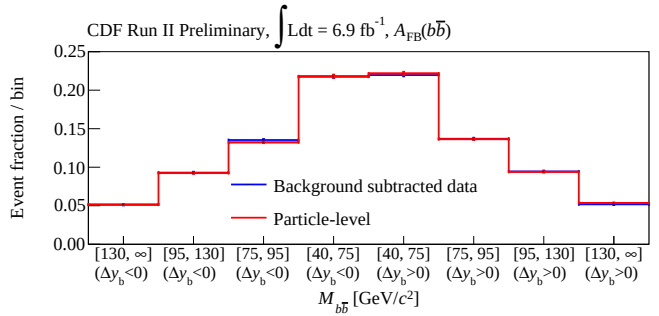


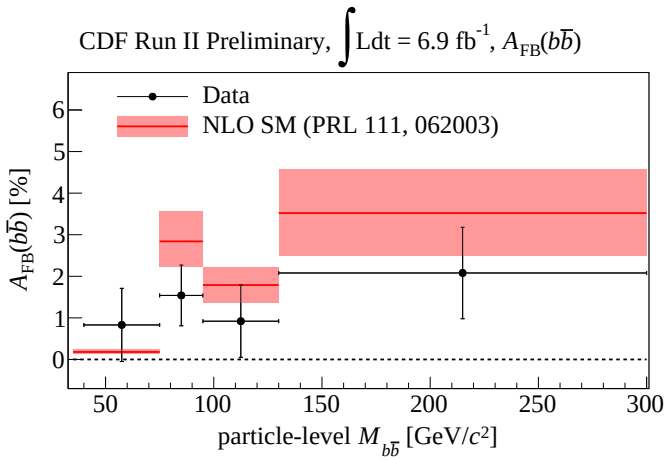


CDF Note 11092

$A_{FB}^{b\bar{b}}$ at low mass

- Require a muon inside one b-jet and use it to identify quark charge
- Measure $A_{FB}^{b\bar{b}}$ in four $b\bar{b}$ mass bins:
  [40, 75], [75, 95], [95, 130], and [130,∞)
- Use SVD for unfolding
- Result consistent with SM prediction, even some indication that we can see the electroweak A_{FB} at the Z pole



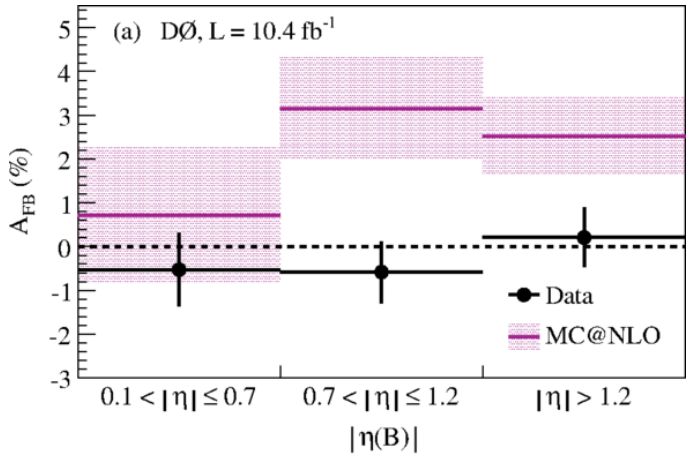


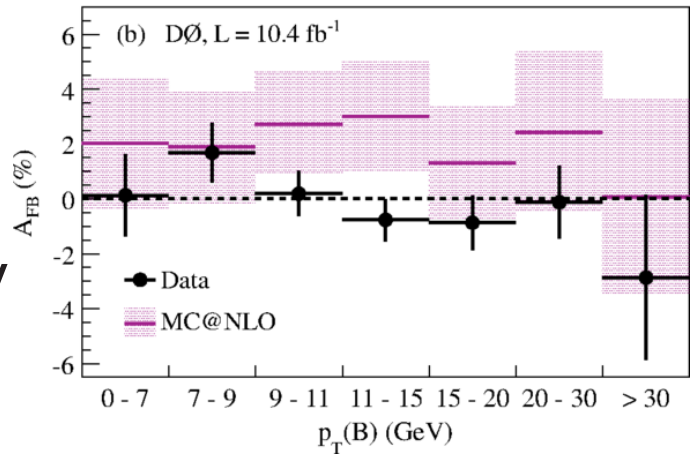
CDF Note 11156

$A_{FB}(B^{\pm})$

$$A_{FB}(B^{\pm}) = -0.24 \pm 0.41(\text{stat}) \pm 0.19(\text{syst})$$

- Reconstruct $B^{\pm} \to J/\psi K^{\pm}$ where $J\psi \to \mu^{+}\mu^{-}$
- $B^{\pm}$ meson collinear with $b(\bar{b})$ quark
- Very low $m_{b\bar{b}}$ scale
- Use unbinned max likelihood fit to extract $A_{FB}(B^{\pm})$
- Result consistent with zero asymmetry
- $\sim 3\sigma$ deviation from MC@NLO
- Suspect deficiency in MC@NLO

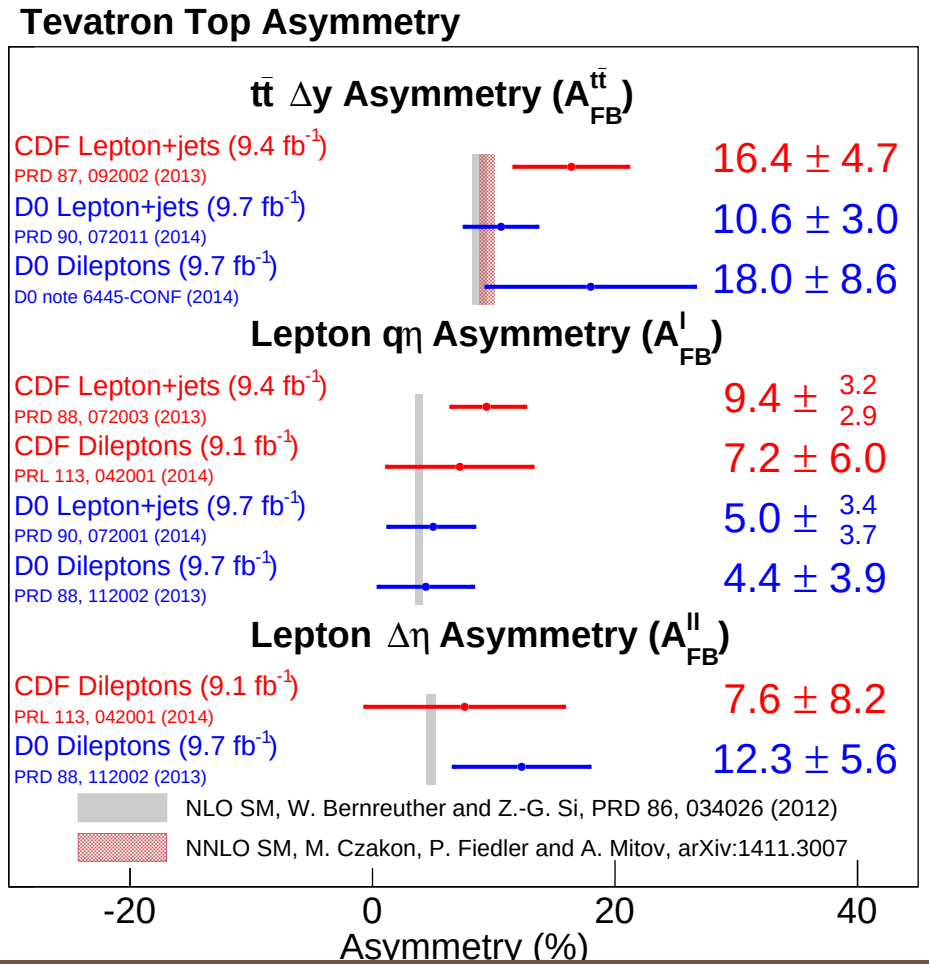




PRL 114, 051803 (2015)

Top (bottom) A_{FB} at Tevatron: Summary

- Results from D0 consistent with SM predictions
- CDF inclusive A_{FB} slightly higher than predictions (1.5σ), differential A_{FB} higher than predictions at 2σ level
- All results higher than quoted SM calculations
- Last measurement from CDF dilepton channel nearing completing
- Expect final Tevatron combination soon
- No anomaly shown in $b\bar{b}$ asymmetry



Conclusions

- Has been an exciting chase for new physics, also spurred development of theory techniques
- Motivated $A_{\mathrm{FB}}^{b\bar{b}}$ measurement
- Nearly completed the legacy A_{FB} measurements for top and bottom quarks at the Tevatron
  - CDF dilepton channel $A_{\mathrm{FB}}^{t\bar{t}}$ done soon
- Tevatron combination of $A_{\mathrm{FB}}^{t\bar{t}}$, A_{FB}^{ℓ} and $A_{\mathrm{FB}}^{\Delta\eta}$ in progress and expected to be the final word from the Tevatron on this important topic

CDF & D0 Top Public Webpages

Top Public Webpages

- CDF: http://www-cdf.fnal.gov/physics/new/top/top.html
- D0: http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

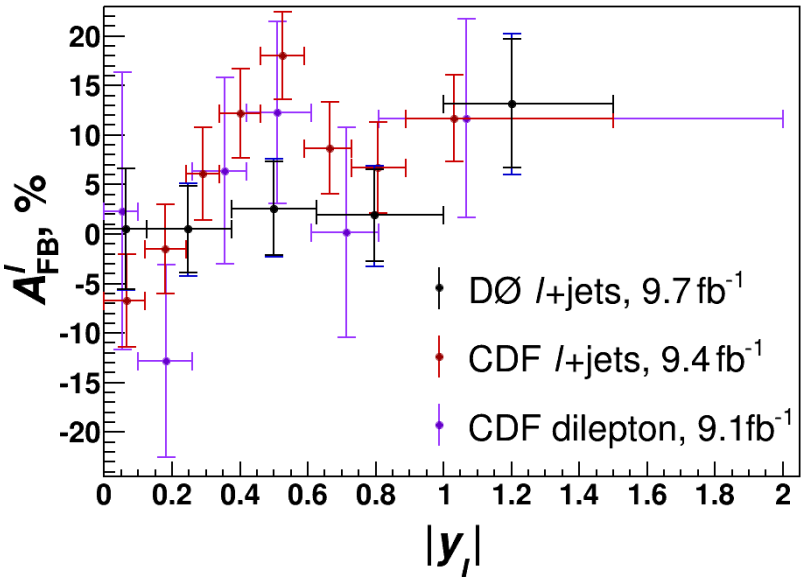
Thank you for your attention and thanks to the organizers for their kind hospitality

Backup Slides

Backup slides

Differential A_{FB} at Tevatron

- Differential A_{FB} show mostly good agreement between CDF and D0 measurements, but some areas under study



$$A_{FB}^{\ell}(|\eta_\ell|)$$